RESEARCH ARTICLE

J. For. 115(6):522–529
https://doi.org/10.5849/JOF-2016-022R2

silviculture

Managing an Established Tree Invader: Developing Control Methods for Chinese Tallow (*Triadica sebifera*) in Maritime Forests

Lauren S. Pile, G. Geoff Wang, Thomas A. Waldrop, Joan L. Walker, William C. Bridges, and Patricia A. Layton

Biological invasions by woody species in forested ecosystems can have significant impacts on forest management and conservation. We designed and tested several management options based on the physiology of Chinese tallow (*Triadica sebifera* [L.] Small). Specifically, we tested four treatments, including mastication, foliar herbicide, and fire ($MH_{fol}F$), mastication and foliar herbicide (MH_{fol}), dormant-stem herbicide and fire ($H_{dor}F$), and dormant-stem herbicide (H_{dor}), to determine their efficacy in reducing the density and regeneration of this highly invasive tree species. Mastication treatments were significant in reducing density the first year but not after 3 years. Prescribed fire significantly reduced density combined with previous treatments. Regeneration coverage was highest on those sites with mastication, which was not affected by the addition of prescribed fire. Overall, we found that the most comprehensive treatment ($MH_{fol}F$) was more effective in reducing density but did not result in a difference in the amount of regeneration after treatment.

Keywords: mastication, herbicide, fire, slash pine

Biological invasions result in a significant challenge to biological conservation and natural resource management, especially when novel ecosystems are created and make the return to natural states difficult (Hobbs et al. 2006). Woody invasive species pose particular management challenges including inhibiting or outcompeting desired species, simplifying natural plant communities, and altering ecological processes, which can ultimately compromise ecological services (Webster et al. 2006). When invasive trees reach high densities, they can greatly increase the biomass or change the type and arrangement of aboveground structure and composition, potentially altering many facets of ecosystem function. The resulting economic impact of forest invaders on timber resources and nonmarket goods and services can be substantial (Holmes et al. 2009).

Chinese tallow (*Triadica sebifera* [L.] Small) is a highly invasive tree species in the southeastern coastal plain of the United States (Bruce et al. 1997). Its high reproductive capacity by seed and vigorous sprouting, rapid growth, tolerance to stressful conditions (Jones and Sharitz 1990; Conner and Askew 1993), ability to suppress fire (Grace et al. 2005), and capacity to establish under intact forest canopies make Chinese tallow a severe threat to forest management and ecosystem integrity. Attempts to manage and control Chinese tallow are often only temporarily effective because of its tenacious ability to regenerate from a persistent seed bank and by root and stump sprouting (Donahue et al. 2006; Enloe et al. 2015). Given the multiple attributes that favor Chinese tallow's successful invasion, approaches that use a combination of methods and tools will probably be required to manage its negative effects and restore natural communities.

This study was motivated by a finding that herbicide alone did not effectively control the growth of the Chinese tallow population in maritime forests at Parris Island

Received July 26 2016; accepted February 13 2017; published online March 23, 2017.

Affiliations: *G. Geoff Wang (gwang@clemson.edu), Department of Forestry and Environmental Conservation, Clemson University, Clemson, SC. Lauren S. Pile (lpile@g.clemson.edu), Clemson University; current affiliation, USDA Forest Service. Thomas A. Waldrop (twaldrop@fs.fed.us), USDA Forest Service. Joan L. Walker (joanwalker@fs.fed.us), USDA Forest Service. William C. Bridges (wbrdgs@g.clemson.edu), Clemson University. Patricia A. Layton (playton@g.clemson.edu), Clemson University.*

Acknowledgments: *This project was funded by Parris Island MCRD, the Department of Defense, and serviced through the Piedmont-South Atlantic Coast – Cooperative Ecosystems Studies Unit and the Army Corps of Engineers – Fort Worth District. We would like to express our deep gratitude to the Natural Resource staff at Parris Island MCRD: John Holloway Jr., Van Horton, and Charles Pinckney, and our field technicians: Steven Broom, Hunter Hadwin, and Matthew Raeckelboom. We would have not completed this work without their hard work and support. We would also like to thank the anonymous reviewers for their comments on earlier versions of the manuscript.*

Marine Corps Recruit Depot (MCRD). Through evaluating the efficacy of various methods to control Chinese tallow in established coastal forests, we proposed several management regimes that combined mastication, prescribed fire, and herbicide treatments to treat stands heavily infested with Chinese tallow. Treatments were designed on the basis of the documented physiology of Chinese tallow and the current condition of the community, that is, with high shrub density that may limit the use of prescribed fire without prior mechanical treatment.

Previous research (Conway et al. 1999) suggested that both the type and timing of individual treatments would influence the efficacy of Chinese tallow control. Total nonstructural carbohydrate (TNC) accumulation in roots is an ecophysiological process (Glerum 1980; Hopkins and Hüner 1995) that is correlated with phenological development and can be used to develop the timing of invasive species treatments (Conway et al. 1999). Based on TNC trends, mastication and herbicide treatments should be applied when the phenological development in Chinese tallow would make their application result in the greatest susceptibility to mortality. Spring application of mastication occurs when Chinese tallow is in active growth, causing the physiological damage to result in less energy available to support new growth and reproduction (James et al. 2010). A thick layer of mulch produced by mastication treatments was also suggested to reduce the germination success of Chinese tallow seeds (Donahue et al. 2004). Both the mastication and herbicide applications would result in increased dead fuel, which would facilitate fire spread, especially where Chinese tallow is abundant (Grace et al. 2005). In addition, the wood of Chinese tallow has been found to be highly ignitable and combustible, which may contribute to fire behavior after mastication (Tiller 2015).

We sought to evaluate the effects of treatment combinations for their short-term impacts on Chinese tallow abundance and recovery and for their ability to establish a frequent fire return interval. We tested four treatments series, including mastication, foliar herbicide and fire ($MH_{fol}F$), mastication and foliar herbicide (MH_{fol}), dormant-stem herbicide and fire ($H_{dor}F$), and dormant-stem herbicide only (H_{dor}), to determine their efficacy on Chinese tallow control. We hypothesized the following: that mastication would reduce Chinese tallow density and facilitate the spread of prescribed fire; that prescribed fire would reduce Chinese tallow density by targeting any stems and regeneration that survived or established after previous treatments; and that the $MH_{fol}F$ treatment would be the most effective for reducing Chinese tallow density and regeneration.

Methods

Site and Study Description

The study was located at Parris Island MCRD in Beaufort County, South Carolina. Parris Island MCRD consists of 8,095 ac, with vegetation dominated by mixed maritime forest and saltwater marsh. Dominant overstory species include slash and loblolly pine (*Pinus elliottii* Engelm. and *Pinus taeda* L.), live oak (*Quercus virginiana* Mill.), sweetgum (*Liquidambar styraciflua* L.), and blackgum (*Nyssa sylvatica* L.). Chinese tallow has been managed on Parris Island MCRD since 2001 through the use of several herbicide formulations, primarily with "hack and squirt" methodology. In 2010, a survey was conducted for invasive species presence and abundance on Parris Island MCRD to assess the effectiveness of previous control efforts. Results from this survey suggested that a more effective management approach was needed, because the Chinese tallow population in some areas had increased despite repeated herbicide applications (Pile 2011). Four experimental treatments defined by combinations of up to three management actions were applied in areas ranging from 1.2 to 5 ac in size (Figure 1).

The $MH_{fol}F$ was designed as a comprehensive treatment series with three treatments applied in a sequence whereby each treatment generates favorable conditions for the next (Figure 2). We applied the mastication treatment in the spring when TNC levels were suspected to be lowest in roots and herbicide applications in the fall and winter when roots were expected to be a TNC sink (Conway et al. 1999). Mastication was conducted in both $MH_{fol}F$ and MH_{fol} using a Caterpillar HM315 mulcher with fixed carbide teeth on a cylindrical rotating drum with hydraulic controls. The treatment was applied in May 2013 to reduce Chinese tallow as well as to reduce understory shrub density, leaving large, well-formed native tree species as seed sources. The operator was instructed to minimize the amount of soil disturbance. Because of the limits of the masticator, any Chinese tallow stems larger than approximately 6 in. dbh were felled with a chainsaw. The mastication treatments were followed by a late summer (September 2013) foliar application of 2.5% v/v Garlon 4 Ultra herbicide targeting any regrowth (i.e., basal sprouts, stump sprouts, and root sprouts) or seedlings. In units without mastication ($H_{fol}F$ and H_{fol}), two types of dormant stem herbicide applications were applied during the winter of 2013 and the treatment varied based on the size of the stem. On individuals less than 6 in. dbh, a basal bark herbicide application of 25% Garlon 4 Ultra and basal oil was applied to the lower portion of the stem (bottom 12–16 in. including rootcollar). On stems greater than 6 in. dbh, the same herbicide mixture was applied but using injection methods ("hack and squirt"). Growing season prescribed fire in combination with mastication and herbicide should further reduce the competitive vigor of Chinese tallow

Management and Policy Implications

Chinese tallow is a highly invasive tree species in the southeastern coastal plain, USA. Chinese tallow invasions can displace native species, potentially having substantial economic impacts on timber resources and desirable forest diversity. Attempts to manage and control Chinese tallow with single treatments are often only temporarily effective because of its ability to regenerate from a persistent seed bank and by root and stump sprouting. In this study, we developed and tested a multiple-treatment regime using mastication and herbicide treatments followed by prescribed burning to reestablish this important ecological process. Individual treatments were timed and sequenced to reduce Chinese tallow densities when they were physiologically most susceptible to further limit their regrowth and new seedling establishment. Long-term control will require additional burning or treatments before seedlings escape to larger size classes. Therefore, effective management of Chinese tallow requires a forward-thinking, integrated approach that aims not only to reduce or exclude the invader but also to restore the affected community by building resistance to future invasion. Furthermore, in the selection of invasive species management practices, the prevention of future invasion must be considered because management actions themselves are disturbance events and many invasive species thrive in disturbed environments.

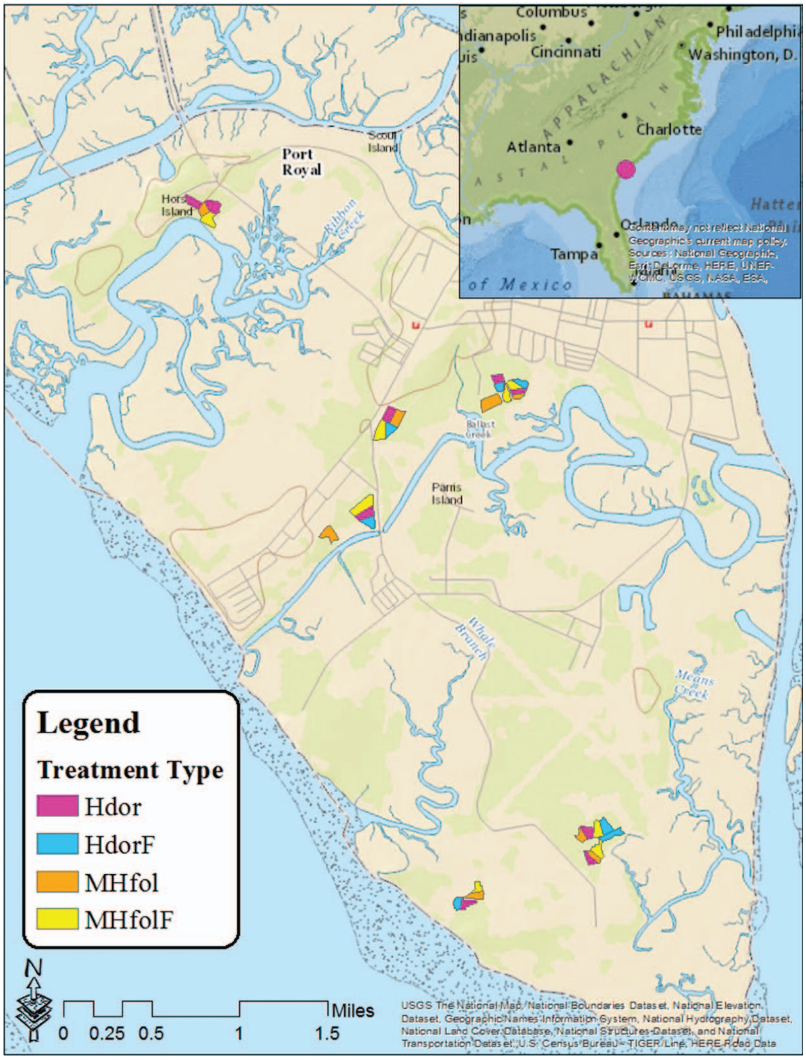

Figure 1. Map of treatment areas ($MH_{fol}F$, MH_{fol}, $H_{dor}F$, and H_{dor}) at Parris Island MCRD, located in Beaufort, South Carolina.

and provide for long-term control. To minimize resprouting and regeneration following the previous two treatments, the prescribed fire treatment was also applied in the spring when TNC levels are the lowest in roots. The prescribed fire treatment was applied in May 2015 in the $MH_{fol}F$ and MH_{fol}. Fires were applied as strip head fires approximately 30 ft apart.

We designed the $H_{dor}F$ treatment to determine whether results similar to those for the $MH_{fol}F$ treatment could be obtained without mastication. The H_{dor} treatment served as our control, as it was how Chinese tallow had been previously managed on Parris Island MCRD and is a common approach to targeted invasive species management. Although this does not serve as an untreated control, data from the H_{dor} treatment, along with the pretreatment survey data, provide a statistical comparison to determine the efficacy of the different treatment types against the standard practice for the management of Chinese tallow.

Site Selection and Plot Description

The study was conducted as an unbalanced (due to one block not receiving all four treatment types) randomized block design, blocked by forest stand with eight replicates and four treatment types, resulting in 32 total experimental units. In Block 2, prescribed burning could not be implemented in an $H_{dor}F$ treatment type, resulting in it being classified as an H_{dor} treatment. Block 2 consisted as the following treatment series: 1 $MH_{fol}F$, 1 MH_{fol}, and 2 H_{dor}; otherwise each block contained 1 $MH_{fol}F$, 1 MH_{fol}, 1 $H_{dor}F$, and 1 H_{dor}. Forest stands at Parris Island were selected based on size (greater than 5 ac), abundant Chinese tallow as determined from survey data collected in 2010 and minimal impact from military training during the treatment period.

A 65.6 × 131.2 ft sample plot was established in each treatment area. Sampling plots were established at least 66 ft from the forest edge and must have also had reproductively mature Chinese tallow within the unit. All Chinese tallow trees greater than 1 in. dbh were measured across the entire sample plot. All sapling-sized Chinese tallow greater than 4.5 ft tall but less than 1 in. dbh were measured in four randomly selected 32.8 × 32.8 ft subplots. Trees and saplings were scaled to a per acre basis and pooled across the sample unit to give density per acre. In the middle of each subplot (8 total), a 3.3 × 3.3 ft quadrat was established, and all regeneration less than 4.5 ft tall was recorded by Braun-Blanquet's cover class (<0.1, 0–1%, 1–2%, 2–5%, 5–10%, 10–25%, 25–50%, 50–75%, 75–95%, and >95%)(Westhoff and Van Der Maarel 1978). A pretreatment survey was conducted in June through August 2012 (Figure 3). A resurvey of only the mastication treatment plots was conducted in July and August 2013 and two complete resurveys of all treatment types were conducted in July and August 2014 and 2015.

Fuels and Prescribed Fire Measurements

We collected surface fuels from 12 11.8 in. × 11.8 in. fuel sample units established around the perimeter of each sample plot in March 2015, 2 years after the mastication treatment and just before the prescribed fire treatment. Fuel samples were collected, bagged, and oven dried at 176° F for 48 hours (Figure 4). Fuels were separated into litter (pine straw, leaves, and palmetto fronds) and three downed woody diameter classes (1 hour: 0–0.25 in., 10 hour: 0.25–1 in., and 100 hour: 1–3 in.) and weighed. The larger 1,000-hour fuels (>3 in.) were measured along three 50-ft transects within each experimental unit (Brown 1974). Each 1,000-hour fuel that crossed the transect was recorded by species, diameter (measured at the transect location), and decay class (i.e., solid, rotten, and very rotten) following Brown (1974). The exception was Chinese tallow, as standard dry biomass equations do not exist for this species. Using a regression equation derived from the mass of stem sections taken in the field at predetermined intervals (0, 11.8, 23.6, 35.4, and every 19.7 in. thereafter) and oven dried to a constant dry weight, we were able to approximate the

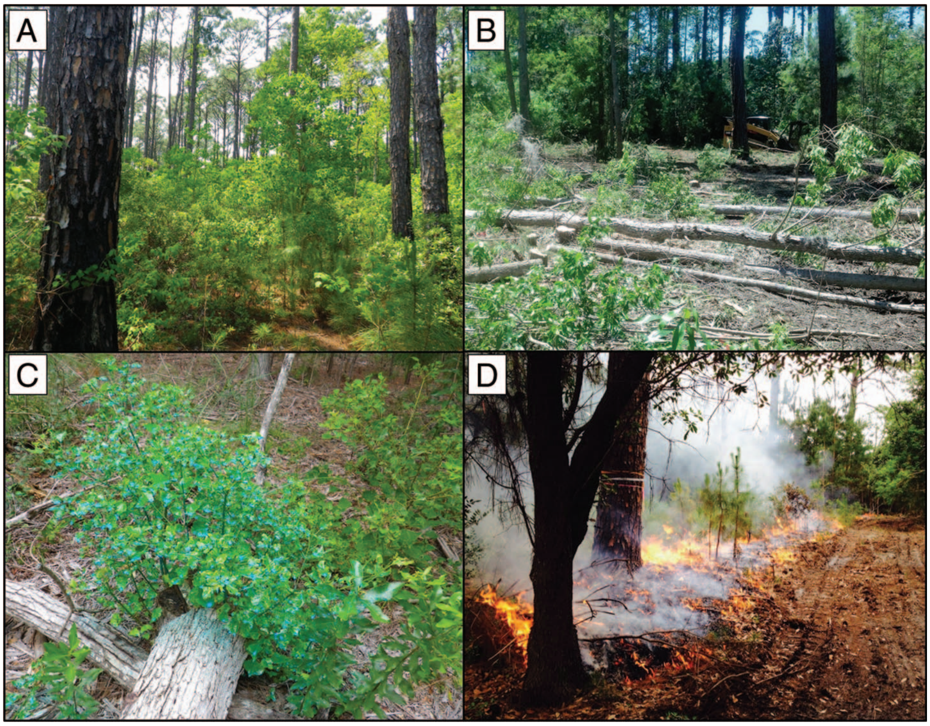

Figure 2. Depiction of the mastication, herbicide, and fire ($MH_{fol}F$) treatment type. A. Forest stands at Parris Island MCRD were dominated by a slash pine (*Pinus elliottii*) overstory with a dense shrub understory. B. The mastication treatment was applied in the spring to reduce Chinese tallow (*Triadica sebifera*) and understory density. C. A fall foliar application of herbicide was applied in the same year to target Chinese tallow regeneration. D. Two years after mastication, a growing season prescribed fire was applied.

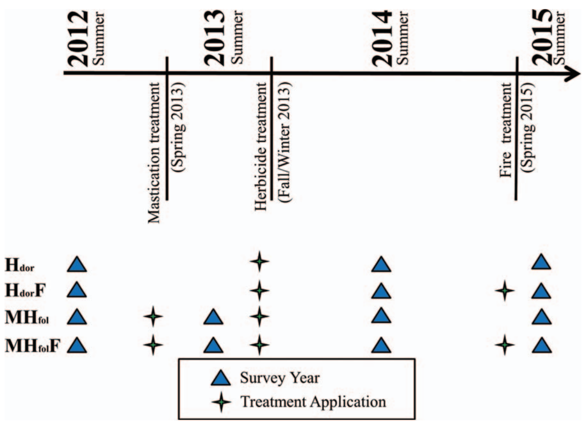

Figure 3. Vegetation survey and treatment timeline at Parris Island. A pretreatment survey occurred in the summer of 2012. The mastication treatment occurred in May 2013. In summer 2013, the masticated treatment areas were re-surveyed. In the late-summer/fall 2013, a foliar application of herbicide was applied to masticated treatment areas. In fall/winter 2013, a dormant application of herbicide (basal bark or "hack and squirt") was applied to the stems of Chinese tallow in nonmasticated stands. A resurvey of all treatment areas was completed in the summer of 2014. The prescribed fire treatment was performed in May 2015, followed by a complete resurvey of all treatment areas in summer 2015.

mass of a log from its calculated volume based on the mass, diameter, and thickness of each cross section (Supplemental Appendix S1^S^). To determine degree of litter and duff consumption, as an approximate measure of fire severity, we placed eight 60-penny nails in the middle of each subplot level with the litter layer and eight additional nails level with the duff layer in each experimental unit. After the fire treatment, the degree of litter and duff consumption was indexed by the length of the nail exposed after burning.

Fuel moisture measurements were obtained before ignition, and weather was monitored before and after ignition (Supplemental Appendix S2). To measure fire temperature, we used temperature-sensitive paints applied to metal tags, each painted with 10 different paints (Tempilaq; Tempil Division, Air Liquide America Corporation) that melt at a different temperatures: 225, 300, 399, 487, 601, 705, 1,000 1,200 1,450, and 1,600 °F and placed in 12 random locations throughout each experimental unit. Each tag was hung from a metal stake approximately 4 in. from the ground. To determine percent area burned within each experimental unit, we established 10 transect lines and point sampled at 3.3-ft intervals, resulting in 260 sample points per unit. The total number of sample points that burned was divided by the total sample points.

Data Analysis

Data were analyzed using JMP, version 11 (SAS Institute, Inc., Cary, NC, 1989–2007) or SAS 9.1.3 (SAS Institute, Inc.). Data are reported as means and SEM. Where appropriate, data were transformed to meet the assumptions of hypothesis testing (i.e., normality and constant variance). Percent coverage of regeneration was determined as the midpoint of each coverage class; for example, 5–10% cover was given a value of 7.5% and was pooled and averaged across the experimental unit. Any P value of ≤ 0.05 was considered evidence of a significant difference.

Initial Effect of Mastication. To determine the effect of mastication on Chinese tallow density, we compared pretreatment data in 2012 with postmastication treatment data in 2013 in mastication treatment plots ($MH_{fol}F$ and MH_{fol} only). Plots without mastication ($H_{dor}F$ and H_{dor}) were not sampled in 2013. A statistical model was developed and contained terms for treatment, block, and year and their interactions, with block included as a random effect. An analysis of variance (ANOVA) was used to develop F statistics to test the model terms.

Mastication on Fire Behavior. To determine the overall effect of mastication on fuel characteristics and fire behavior, we compared treatment type based on samples taken and averaged across each experimental

S Supplementary data are available with this article at https://doi.org/10.5849/jof.2016-022.

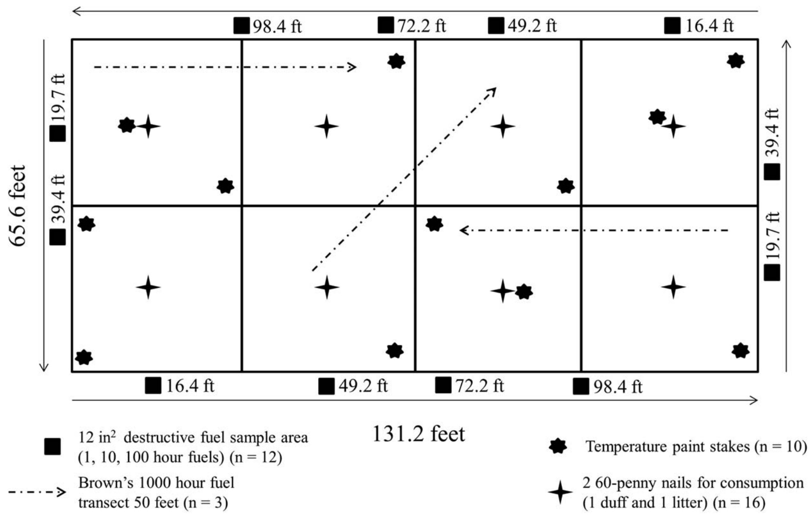

Figure 4. Depiction of fuels and fire sampling method within each experimental unit receiving a fire treatment ($MH_{fol}F$ and $H_{dor}F$).

Table 1. Means of pretreatment fuel depth, fuel load, and posttreatment consumption by treatment type at Parris Island MCRD, South Carolina.

	Fuel depth		Fuel load						Consumption	
Treatment	Litter depth	Duff depth	Litter	1-hr	10-hr	100-hr	1000-hr	Total fuels	Litter (in.)	Area burned (%)
	. . . .(in.). . . .		. . . .(ton ac^{-1})							
$H_{dor}F$ (7)	2.1	0.7	9.87	0.54	1.03	0.27	4.33	15.97	0.7	67.9
$MH_{fol}F$ (8)	2.2	0.8	10.08	1.16	2.90	0.71	4.82	19.67	0.7	74.2
P value	0.77	0.35	0.89	0.01	0.01	0.16	0.89	0.42	0.98	0.63

Table 2. Overall treatment effect and the effect of treatment type by linear contrast across survey years.

Treatment	Density (trees/ac)	Regeneration (% cover)
H_{dor}	89 ± 0.65	0.89 ± 0.21
$H_{dor}F$	55 ± 0.68	0.85 ± 0.24
MH_{fol}	61 ± 0.67	1.71 ± 0.23
$MH_{fol}F$	19 ± 0.67	1.31 ± 0.23
Treatment	$P = 0.047$	$P = 0.009$
Year	$P < 0.001$	$P = 0.458$
Treatment × year	$P = 0.008$	$P = 0.273$
Mastication	$P = 0.063$	$P = 0.002$
Fire	$P = 0.039$	$P = 0.291$
MHF treatment	$P = 0.011$	$P = 0.441$

Mastication = $MH_{fol}F$ and MH_{fol} versus $H_{dor}F$ and H_{dor}; Fire = $MH_{fol}F$ and $H_{dor}F$ versus MH_{fol} and H_{dor}; MHF = $MH_{fol}F$ versus MH_{fol}, $H_{dor}F$, and H_{dor}.

unit, and an ANOVA as discussed above (without the effect of year, and its interaction) was used to analyze differences between fire treatment types.

Effect of Treatment Series. To determine the overall effect of all treatment types on Chinese tallow abundance, we compared treatment types across years (2012, 2014, and 2015). We did not include 2013 in the model as it was an incomplete survey year across all treatments (the 2013 survey only recorded the effects of the mastication treatment on $MH_{fol}F$ and MH_{fol} treatment types). Using an ANOVA, we modeled treatment, block, and year and their interactions with block as a random effect in the model. We also assessed the effect of the treatments within the survey year and followed-up with specific linear contrasts as discussed below.

Linear Contrasts of Treatment Type. From the ANOVA determining the overall effect on Chinese tallow abundance, we constructed specific linear contrasts to test for effects of treatment components, specifically to determine the effect of mastication, fire, and the $MH_{fol}F$ treatment type. To determine the effect of mastication, we compared mastication treatments ($MH_{fol}F$ and MH_{fol}) to those without mastication ($H_{dor}F$ and H_{dor}). To determine the effect of fire, we compared fire treatments ($MH_{fol}F$ and $H_{dor}F$) to those without fire ($M_{fol}H$ and H_{dor}). To determine whether $MH_{fol}F$ was statistically significant in reducing Chinese tallow, we compared it to all other treatment types (MH_{fol}, $H_{dor}F$, and H_{dor}). In addition, similar contrasts were conducted by survey year to determine the effects of treatment within year. Specifically, we assessed 2014 to determine the effect of mastication and 2015 to determine the effect of mastication, fire, and the $MH_{fol}F$ treatment.

Results

Before treatment, there were no significant differences among any of the treatment areas in Chinese tallow density (overall mean, 481 ± 149 trees per ac [TPA]; $F = 2.02$; $P = 0.14$), basal area (overall mean, 14.7 ± 5.01 ft^2; $F = 2.06$; $P = 0.15$), or percent coverage of regeneration (overall mean 1.36 ± 0.34%; $F = 1.22$; $P = 0.33$).

Initial Effect of Mastication

Immediately after mastication, the density of Chinese tallow was significantly reduced from pretreatment in 2012 to posttreatment in 2013 ($F = 62.83$; $P < 0.01$). Average density within mastication treatment units ($MH_{fol}F$ and MH_{fol}) was 811 ± 107 TPA before treatment in 2012 but was reduced to 24 ± 107 TPA after mastication. Coverage of regeneration was 1.7% before treatment and 2.6% after mastication; however, this difference was not significant ($F = 2.34$; $P = 0.15$).

Mastication Effect on Fire Behavior

Percent area burned and average fire temperature were not affected by mastication treatment ($F = 0.2$; $P = 0.63$ and $F = 0.1$; $P = 0.82$, respectively) (Table 1). Two growing seasons after mastication, fuel bed depths, amount of litter, and 100- and 1,000-hour fuels did not differ between mastication and unmasticated treatment types. However, mastication treatments had higher 1- and 10-hour fuel loading than those without mastication ($F = 8.29$; $P = 0.01$ and $F = 9.3$; $P < 0.01$, respectively). Average fire temperature was 385 ± 149° F. Average fire temperature was not significantly different between masticated treatment areas (392 ± 75° F) and nonmasticated areas (376 ± 77° F; $F = 0.05$; $P = 0.82$). The amount of litter consumed from fire did not differ between treatment types ($H_{dor}F = 0.67 \pm 0.15$ in.; $MH_{fol}F = 0.67 \pm 0.14$ in.; $F < 0.01$; $P = 0.98$). Only one experimental unit had any measurable consumption of duff, which occurred at only one of the eight sample points within one experimental unit and subsequently was not analyzed.

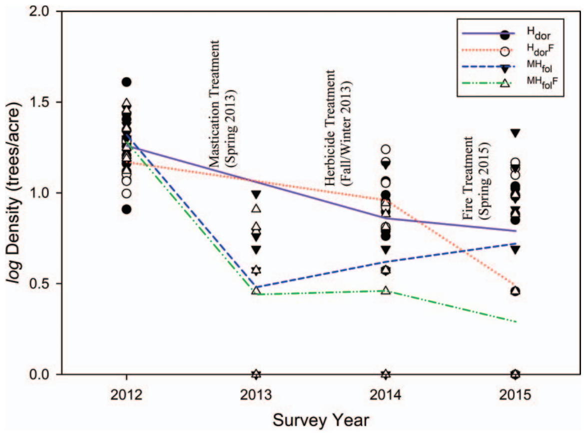

Figure 5. Overall effect by treatment in each year on the density (log TPA) of Chinese tallow at Parris Island.

Table 3. Effect of treatment type compared within the survey year.

Treatment and effect	Year 2012	2013[1]	2014	2015
H_{dor}				
Density (trees/ac)	1,001 ± 266	NA	76 ± 34	80 ± 55
Basal area (ft^2/ac)	15.3 ± 9.2	NA	3.5 ± 1.3	0.9 ± 0.9
Regeneration (% cover)	0.98 ± 0.6	NA	0.67 ± 0.35	1.17 ± 0.28
$H_{dor}F$				
Density (trees/ac)	392 ± 287	NA	162 ± 36	111 ± 60
Basal area (ft^2/ac)	9.6 ± 6.5	NA	1.7 ± 1.3	1.3 ± 0.9
Regeneration (% cover)	1.08 ± 0.6	NA	0.71 ± 0.37	0.82 ± 0.27
MH_{fol}				
Density (trees/ac)	841 ± 266	27 ± 12	49 ± 34	160 ± 56
Basal area (ft^2/ac)	18.7 ± 6.1	1.7 ± 0.9	1.7 ± 1.3	1.3 ± 0.9
Regeneration (% cover)	2.19 ± 0.6	3.0 ± 0.6	1.69 ± 0.35	1.0 ± 0.25
$MH_{fol}F$				
Density (trees/ac)	780 ± 266	20 ± 12	20 ± 34	22 ± 56
Basal area (ft^2/ac)	14.8 ± 6.1	0.4 ± 0.9	0.3 ± 1.3	0.1 ± 0.9
Regeneration (% cover)	1.18 ± 0.6	2.62 ± 0.6	1.56 ± 0.35	1.19 ± 0.25
Density (trees/ac)				
Effect of M			$F = 18.2$; $P < 0.01$	$F = 0.72$; $P = 0.4$
Effect of F				$F = 5.4$; $P = 0.03$
M + F				$F = 4.3$; $P = 0.05$
Basal area (ft^2/ac)				
Effect of M			$F = 2.5$; $P = 0.13$	$F = 0.38$; $P = 0.5$
Effect of F				$F = 0.22$; $P = 0.6$
M + F				$F = 1.6$; $P = 0.2$
Regeneration (% cover)				
Effect of M			$F = 11.6$; $P < 0.01$	$F = 0.17$; $P = 0.7$
Effect of F				$F = 0.14$; $P = 0.7$
M + F				$F = 0.55$; $P = 0.5$

The mastication treatment occurred in the spring of 2013, the herbicide treatment occurred in the fall of 2014, and the fire treatment occurred in the spring of 2015. Effects of the mastication treatment were analyzed from the 2014 and 2015 survey data, the effect of fire in 2015, and the effect of mastication and fire combination in 2015. H, herbicide; HF, herbicide and fire; MH, mastication and herbicide; MHF, mastication, herbicide, and fire; NA, not applicable.
[1]Survey data in 2013 were only recorded in the mastication treatment units.

Overall Treatment Effect

After two growing seasons, the residual effect of mastication was not significant in reducing the density of Chinese tallow. However, fire and the $MH_{fol}F$ treatment type did result in a significant reduction in the abundance of Chinese tallow. Based on the overall ANOVA for Chinese tallow density (TPA) across the entire survey period, there was a significant interaction between treatment and year ($F = 3.29$; $P = 0.008$), a significant effect of treatment ($F = 3.16$; $P = 0.047$), and a significant effect of year ($F = 57.34$; $P < 0.001$) (Table 2). The interaction between treatment and year was primarily driven by the increase in density in the mastication and foliar herbicide treatments in 2014 and 2015 (Figure 5) and by the effect of mastication and fire treatments occurring in different years. The linear contrast for the effect of mastication treatments against those without mastication ($MH_{fol}F$ and MH_{fol} versus $H_{dor}F$ and H_{dor}) was not significant ($F = 3.85$; $P = 0.06$). The linear contrast to determine the effect of fire ($MH_{fol}F$ and $H_{dor}F$ compared to MH_{fol} and H_{dor}) was significant for reducing Chinese tallow density by 114 ± 90 TPA ($F = 4.8$; $P = 0.04$). When contrasted against all other treatments, the $MH_{fol}F$ treatment was overall effective in reducing Chinese tallow density by 36 ± 102 TPA ($F = 7.73$; $P < 0.01$).

By 2015, mastication resulted in an overall increase in the coverage of Chinese tallow regeneration (stems <4.5 ft tall), but there was no effect of fire or the $MH_{fol}F$ treatment type. Based on the overall ANOVA for the effect of treatment and year on Chinese tallow regeneration coverage, treatment was a significant factor in Chinese tallow regeneration coverage ($F = 4.85$; $P < 0.01$), but there was no effect of year ($F = 0.79$; $P = 0.46$) or interaction between treatment and year ($F = 1.3$; $P = 0.27$). The treatments with mastication had a 0.54 ± 0.21% increase in regeneration coverage compared to those without mastication ($F = 12.81$; $P < 0.01$). Treatments with fire were not significantly different from treatments without fire in promoting or reducing the coverage of Chinese tallow regeneration ($F = 1.16$; $P = 0.29$), nor was the $MH_{fol}F$ treatment different from all other treatment types ($F = 0.61$; $P = 0.44$).

Effect of Treatment Type by Year

Mastication, fire, and the $MH_{fol}F$ treatment had a significant effect on Chinese tallow density and regeneration assessed within the survey year. In 2014, mastication treatments ($MH_{fol}F$ and MH_{fol}) significantly reduced Chinese tallow density by 80 ± 27 TPA ($F = 18.2$; $P < 0.01$) and promoted a 0.91 ± 0.27% increase in regeneration ($F = 11.6$; $P < 0.0$) (Table 3; Figure 6). The application of fire in 2015 resulted in a significant difference between treatments with and without fire ($F = 5.4$; $P = 0.03$); treatments with fire had 30 ± 27 fewer Chinese tallow stems per acre. In 2015, the $MH_{fol}F$ treatment resulted in 69 ± 31 fewer TPA than all other treatments ($F = 4.3$; $P = 0.05$).

Discussion

Management strategies to control invasive species often are developed using only a top-down approach, specifically targeting the invading species through mastication,

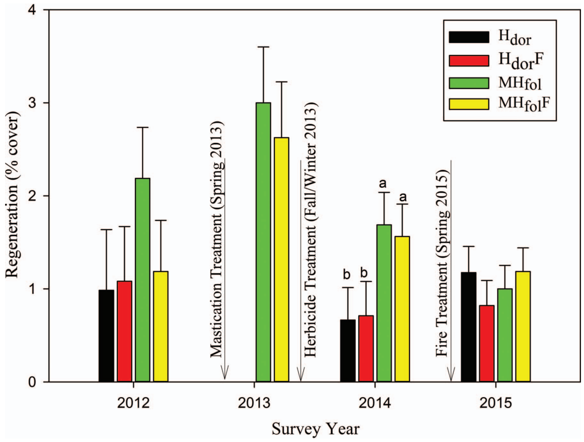

Figure 6. Effect of treatment within year on Chinese tallow regeneration; different letters indicate a significant difference ($P < 0.05$) among treatment types.

herbicide, and biological control or controlling the spread of propagules (D'Antonio and Chambers 2006). We used a top-down approach for targeting the physiology of Chinese tallow through the use of herbicide, mastication, and fire, with the concept that fire may provide a long-term approach to reducing establishment and growth once the population has been reduced with previous treatments. Bottom-up controls are those that emphasize the application of properties and processes that contribute to the resilience and resistance of the invaded community (McEvoy and Coombs 1999). Often invasive plant management can enhance invasibility through resource release and decreased competition (Thompson et al. 2001; Minchinton and Bertness 2003), resulting in the reinvasion of the plant targeted for control or the colonization by a new invasive plant (Kettenring and Adams 2011). Frequent surface fire may act as a long-term top-down control strategy for managing Chinese tallow and may also drive bottom-up community processes. In communities that are adapted for this type of fire regime, using fire to promote fire-tolerant plant species may contribute to fine fuel loading and increased competition among species.

Mastication is a common treatment to reallocate vertical fuels onto the ground surface to reduce fire hazard and improve resilience to future fires (Kreye et al. 2014). However, the use of mastication as a management tool for invasive species has been minimally evaluated, specifically because of the concern for aggressive sprouting in many woody invasive species (e.g., Chinese privet [*Ligustrum sinense* Lour.] and tree-of-heaven [*Ailanthus altissma* (Mill.) Swingle]). In our study, we used mastication not only to reduce Chinese tallow and understory shrub density but also to increase the horizontal continuity of the fuel bed. Chinese tallow is considered a fire suppressor (Grace 1998), because its litter decomposes more rapidly than the litter of native southeastern species, resulting in reduced surface fuel loading (Cameron and Spencer 1989). However, we did find that Chinese tallow regeneration increased after mastication, suggesting that mastication should not be used without additional treatments to achieve control.

The insignificant effects of mastication on aspects of the prescribed burn behavior may be explained by the fire weather condition when the burn was conducted. In the month before burning (April 2015), the area received 14 in. of rain (National Oceanic and Atmospheric Administration 2015), which probably impeded fire spread and resulted in low fire temperatures. Clearly, wet fuel conditions became the most limiting factor affecting fire behavior and fire effects, making any effect of mastication on fire behavior difficult to detect. Our fires may not have produced the level of desired impact on Chinese tallow as hotter, more intense fires may have.

We applied growing season prescribed fire as a part of our treatment series to control Chinese tallow, because prescribed fire is expected to have the greatest impact on Chinese tallow when it is conducted during the growing season (Grace et al. 2005). The effect of growing season prescribed fire on woody species may be more damaging or stressful to underground organs because of greater fire intensity (Johnson 1992) or because the carbohydrates needed for resprouting are diminished as they reside in aboveground portions that are killed, and frequent, growing season fires can deplete carbohydrate reserves (Matlack et al. 1993). However, sprouting capacity after repeated topkill has not been studied in Chinese tallow, and the effect of frequent prescribed burning treatments will need to be studied.

The $MH_{fol}F$ treatment was most effective in reducing Chinese tallow density. By decreasing the overall stem density across the treatment unit with mastication, a follow-up treatment with herbicide became a much easier operation than in areas where mastication was absent. Chinese tallow regeneration was promoted by mastication. Although mulch depths were not measured after the treatment, a large number of seedlings emerged and appeared to be stimulated by the treatment. Donahue et al. (2004) suggested that a thick layer of mulch produced by mastication treatments may reduce the germination of Chinese tallow seeds; however, the mulch levels in this study may have not been thick enough to produce this effect. The foliar herbicide treatment was applied 5 months after mastication, targeting Chinese tallow regeneration. However, there may have been limitations to the foliar herbicide application, as some larger diameter stems may have not produced enough foliar biomass within the 5-month period to allow for effective herbicide uptake to kill the extensive root system of large individuals. Although fire did not reduce regeneration significantly below that of other treatments, it did suppress an increase in regeneration from the mastication treatment, which effectively prevented regeneration recruitment into larger size classes. Indeed, without the added fire treatment, the $M_{fol}H$ treatment had an increase in stem density across the experimental units from 2014 to 2015. Although the implications for our study on the effect of prescribed fire should be considered cautiously because of the short time frame between the fire treatment and the postsurvey treatment findings, these results suggest that a frequent surface fire regime would be necessary to keep future Chinese tallow invasion in check. In addition, until the seed source in the area is diminished, prescribed fire may expose mineral soil, providing an opportunity for new seedling establishment after fire treatment.

Chinese tallow is sensitive to fire at smaller diameters, and the repeated use of prescribed fire may reduce the establishment of Chinese tallow in these stands, promote native understory species and tree regeneration, and reduce shrub density. Without fire for even short periods, Chinese tallow may become established in high densities and grow to diameters where increased bark thickness aids in fire tolerance, resulting in a need for alternative treatments before the establishment of frequent, prescribed fires. Because Chinese tallow is able to reach reproductive maturity in 3 years, fire return intervals should be short enough to maintain any regeneration of Chinese tallow in juvenile stages to reduce seed supply.

In this study, we used the physiology of Chinese tallow to develop testable control methods that were available and applicable to management and were based on current site conditions. We considered frequent prescribed fire as an option for long-term control of Chinese tallow that may also promote other ecosystem functions and incorporate it into experimental treatments. Mastication provided a starting point for the application of additional treatments and herbicide provided a targeted approach to reducing the population with the objective of having minimal impact on other species. Prescribed fire or mastication may not be an option in all communities in which Chinese tallow invades, especially in bottomland communities or sensitive areas. However, developing a multifaceted approach to invasive species management will require knowing the tools available for management and how to use them and in what sequence to have the greatest efficacy for the target species and under what site-specific conditions the community is governed.

Literature Cited

Brown, J.K. 1974. *Handbook for inventorying downed woody material*. USDA Forest Service, Gen. Tech. Rep. INT-16, Intermountain Forest and Range Experiment Station, Ogden, UT. 24 p. https://www.treesearch.fs.fed.us/pubs/28647.

Bruce, K.A., G.N. Cameron, P.A. Harcombe, and G. Jubinsky. 1997. Introduction, impact on native habitats, and management of a woody invader, the Chinese tallow tree, *Sapium sebiferum* (L.) Roxb. *Nat. Areas J.* 17(3):255–260. https://www.researchgate.net/publication/279903278_Introduction_impact_on_native_habitats_and_management_of_a_woody_invader_the_Chinese_tallow_tree_Sapium_sebiferum_L_Roxb.

Cameron, G.N., and S.R. Spencer. 1989. Rapid leaf decay and nutrient release in a Chinese tallow forest. *Oecologia* 80(2):222–228. doi:10.1007/BF00380155.

Conner, W.H., and G.R. Askew. 1993. Impact of saltwater flooding on red maple, redbay, and Chinese tallow seedlings. *Castanea* 58(3):214–219. http://www.jstor.org/stable/4033645.

Conway, W.C., L.M. Smith, R.E. Sosebee, and J.F. Bergan. 1999. Total nonstructural carbohydrate trends in Chinese tallow roots. *J. Range Manage.* 52(5):539–542. doi:10.2307/4003784.

D'Antonio, C.M., and J.C. Chambers. 2006. Using ecological theory to manage or restore ecosystems affected by invasive plant species. P. 260–279 in *Foundations of restoration ecology*, Falk, D.A., M.A. Palmer, and J.B. Zedler (eds.). Island Press, Washington, DC.

Donahue, C., W.E. Rogers, and E. Siemann. 2004. Effects of temperature and mulch depth on Chinese tallow tree (*Sapium sebiferum*) seed germination. *Texas J. Sci.* 56(4):347–356. https://www.researchgate.net/publication/289791964_Effects_of_temperature_and_mulch_depth_on_Chinese_tallow_tree_Sapium_sebiferum_seed_germination.

Donahue, C., W.E. Rogers, and E. Siemann. 2006. Restoring an invaded prairie by mulching live *Sapium sebiferum* (Chinese tallow trees): Effects of mulch on *Sapium* seed germination. *Nat. Areas J.* 26(3):244–253. doi:10.3375/0885-8608(2006)26[244:RAIPBM]2.0.CO;2.

Enloe, S.F., N.J. Loewenstein, D. Streett, and D.K. Lauer. 2015. Herbicide treatment and application method influence root sprouting in Chinese tallowtree (*Triadica sebifera*). *Invas. Plant Sci. Manage.* 8(2):160–168. doi:10.1614/IPSM-D-14-00062.1.

Glerum, C. 1980. Food sinks and food reserves of trees in temperate climates. *N.Z. J. For. Sci.* 10:176–185. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.727.8646.

Grace, J.B. 1998. Can prescribed fire save the endangered coastal prairie ecosystem from Chinese tallow invasion? *Endangered Species Update* 15(5):70–76. https://www.researchgate.net/publication/245601355_Can_prescribed_fire_save_the_endangered_coastal_prairie_ecosystem_from_Chinese_tallow_invasion.

Grace, J.B., L.K. Allain, H.Q. Baldwin, A.G. Billock, W.R. Eddleman, A.M. Given, C.W. Jeske, and R. Moss. 2005. *Effects of prescribed fire in the coastal plains of Texas*. Open-File Rep. 2005–1287, US Geological Survey, Reston, VA. 46 p. Available online at https://www.nwrc.usgs.gov/factshts/2005-1287-fire-in-coastal-texas-report.pdf.

Hobbs, R.J., S. Arico, J. Aronson, J.S. Baron, P. Bridgewater, V.A. Cramer, P.R. Epstein, J.J. Ewel, C.A. Klink, and A.E. Lugo. 2006. Novel ecosystems: Theoretical and management aspects of the new ecological world order. *Global Ecol. Biogeogr.* 15(1):1–7. doi:10.1111/j.1466-822X.2006.00212.x.

Holmes, T.P., J.E. Aukema, B. Von Holle, A. Liebhold, and E. Sills. 2009. Economic impacts of invasive species in forests. *Ann. N.Y. Acad. Sci.* 1162:18–38. doi:10.1111/j.1749-6632.2009.04446.x.

Hopkins, W.G., and N.P. Hüner. 1995. *Introduction to plant physiology*. John Wiley & Sons, New York. 464 p.

James, J.J., B.S. Smith, E.A. Vasquez, an R.L. Sheley. 2010. Principles for ecologically based invasive plant management. *Invas. Plant Sci. Manage.* 3(3):229–239. doi:10.1614/IPSM-D-09-00027.1.

Johnson, E.A. 1992. *Fire and vegetation dynamics*. Cambridge University Press, New York. 144 p.

Jones, R.H., and R.R. Sharitz. 1990. Effects on root competition and flooding on growth of Chinese tallow seedlings. *Can. J. For. Res.* 20(5):573–578. doi:10.1139/x90-074.

Kettenring, K.M., and C.R. Adams. 2011. Lessons learned from invasive plant control experiments: A systematic review and meta-analysis. *J. Appl. Ecol.* 48(4):970–979. doi:10.1111/j.1365-2664.2011.01979.x.

Kreye, J.K., N.W. Brewer, P. Morgan, J.M. Varner, A.M. Smith, C.M., Hoffman, and R.D. Ottmar. 2014. Fire behavior in masticated fuels: A review. *For. Ecol. Manage.* 314:193–207. doi:10.1016/j.foreco.2013.11.035.

Matlack, G.R., D.J. Gibson, and R.E. Good. 1993. Regeneration of the shrub *Gaylussacia baccata* and associated species after low-intensity fire in an Atlantic coastal plain forest. *Am. J. Bot.* 80(2):119–126. https://www.researchgate.net/publication/280842442_Regeneration_of_the_shrub_Gaylussacia_baccata_and_associated_species_after_low-intensity_fire_in_an_Atlantic_Coastal_Plain_forest.

McEvoy, P.B., and E.M. Coombs. 1999. Biological control of plant invaders: Regional patterns, field experiments, and structured population models. *Ecol. Applic.* 9(2):387–401. doi:10.1890/1051-0761(1999)009[0387:BCOPIR]2.0.CO;2.

Minchinton, T.E., and T.D. Bertness. 2003. Disturbance-mediated competition and the spread of *Phragmites australis* in a coastal marsh. *Ecol. Applic.* 13(5):1400–1416. doi:10.1890/02-5136.

National Oceanic and Atmospheric Administration. 2015. *Monthly summaries of GHCN-daily CSV for GHCND:US1SCBF0040—BEAUFORT 4.3 SSE, SC US*. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Silver Spring, MD.

Pile, L. 2011. *Parris Island depot invasive plant species control monitoring*. Department of Forestry and Natural Resources. Clemson Univ., Clemson, SC, p. 54.

Thompson, K., J.G. Hodgson, J.P. Grime, and M.J.W. Burke. 2001. Plant traits and temporal scale: Evidence from a 5-year invasion experiment using native species. *J. Ecol.* 89(6):1054–1060. doi:10.1111/j.1365-2745.2001.00627.x.

Tiller, M.B. 2015. Effects of yaupon, Chinese privet, and Chinese tallow on understory fuel flammability in east Texas hardwood and pine ecosystems. P. 172 in *Natural resource management*. Stephen F. Austin State Univ., Nagadoches, TX.

Webster, C.R., M.A. Jenkins, and S. Jose. 2006. Woody invaders and the challenges they pose to forest ecosystems in the eastern United States. *J. For.* 104(7):366–374. http://www.ingentaconnect.com/contentone/saf/jof/2006/00000104/00000007/art00006.

Westhoff, V., and E. Van Der Maarel. 1978. The Braun-Blanquet approach. P. 287–399 in *Classification of plant communities*. Springer, New York.